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CRACK FORMATION UNDER MONOTONIC CREEP AND CREEP FATIGUE INTERACTIONS AT ELEVATED TEMPERATURES.

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by

10 Ali S. Argon

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CRACK FORMATION UNDER MONOTONIC CREEP AND CREEP FATIGUE INTERACTIONS AT ELEVATED TEMPERATURES

(Final Report Covering period of Feb. 1, 1974 - August 31, 1977 under Contract No. DAHC04 74 C 0008)

I. <u>The Problem:</u> Service fractures at elevated temperature in a high performance structure are usually influenced by a combination of monotonic and cyclic deformation, i.e., by combined creep and fatigue. This research has concentrated on two aspects of this process:

1) Initiation of holes or cracks from interfaces of non-deformable particles either embedded in a continuum that is creeping according to a power law or situated on sliding boundaries, transmitting no shear traction, between two regions which are also creeping according to a power law; initiation of cracks across boundaries due to stress concentrations that arise from adjoining sliding boundaries, that transmit no shear traction - again in a medium that is creeping according to a power law.

2) Interaction of fatigue cracks with previously introduced intergranular creep cracks.

Of these two aspects, the first one was dealt with primarily by theoretical approaches while the second one was investigated experimentally.

II. <u>Summary of Results:</u>

A. <u>Intergranular Hole Formation due to Sliding Boundaries (C. W. Lau):</u>

Two fundamental problems have been investigated in detail.

In the first one, a two-dimensional array of hexagonal grains having boundaries that transmit only normal tractions is considered subjected to tension at a distance. The grain interiors are assumed to be incompressible and to undergo power-law creep with differing power exponents from 1 to 15. Of interest is the nature of the stress

concentration across boundaries normal to the tension direction. The problem has been solved at two levels. The singular solution at the triple junction was obtained by an extension of Hutchinson's (1) method of generalized stress functions of product form having separability between the range dependent term and the angle dependent term. The background solution for the hexagonal grain into which the singular solution is built was obtained by a finite element method in which boundaries were made linearly viscous with a very low viscosity and some linear elasticity was added to the incompressible power law type constitutive behavior of the grain interiors to avoid operational infinities in the computation.

In the second problem, lenticular hard particles were considered on sliding boundaries separating regions creeping according to a power law and again the stress concentration on their interfaces near their apexes was computed in two stages as above. The computations give the following important results for these two fundamental problems:

a) When the non-linearity of the creeping medium increases, characterized by increasing stress exponents in its constitutive behavior, the concentration of stress recedes to the origin of the triple point junction, actual concentrations of stress at physically meaningful distances from the origin decrease while the range of the concentration increases. In the limit as the exponent of the power law goes to infinity to reflect a truly rate independent plastic response, the stress distribution becomes flat near the triple point, as can be expected from analyses of ideal plasticity.

b) As the material behavior becomes more non-linear, the local "smoothing" effect of diffusional flow by Coble Creep along boundaries produces a decreasing alteration on the maximum stress concentration.

A theory for hole nucleation at particle interfaces that considers the first phase as the opening-up of an interfacial crack has been developed after the lines of Stroh 's (2) theory which will utilize the computed stress concentrations in obtaining the local energy release.

B. Interaction of Fatigue Cracks with Intergranular Creep Damage, (J. Gertner):

The terminal phase of interaction of monotonic and cyclic deformation in producing fracture was investigated experimentally in 304 steinless steel.

Large bars of 304 stainless steel with rectangular cross section were strained in tension and bending at 700°C at stress levels to produce extensive intergranular pore and crack formation at local strain rates of the order of 5×10^{-3} per hour. Strips of material containing either quasi-uniformly distributed intergranular creep cracks (crept in tension) or a gradient of intergranular creep crack distribution (crept in bending) were electron-beam welded into tapered fatigue specimens of constant stress intensity factor configurations. Fatigue crack growth rates were then measured in such intergranularly damaged material at both 700°C and room temperature; in both air and vacuum; under conditions where the fatigue cracks propagated either parallel to the planes of the intergranular cracks or perpendicular to them. These experiments led to the following important observations.

a) At 700°C where fatigue cracks grow parallel to intergranular creep cracks, the fatigue crack growth rates decrease by about a factor of 2 for an increase of prior creep strain between 0 and 0.2 where in the latter case about 15% of the final fatigue fracture surface is made up of the previously introduced intergranular creep cracks, and the root mean square roughness of the fatigue fracture surface as much as 60 microns.

b) At room temperature where fatigue cracks grow parallel to the intergranular creep cracks, the fatigue crack growth rates increase by about a factor of 2 for an increase of prior creep strain between 0 and 0.2, producing a root mean square fracture surface roughness of as much as 26 microns.

c) When fatigue cracks propagate perpendicular to the planes of the prior intergranular creep cracks they slow down at both 700°C and room temperature.

d) In all cases, fatigue crack growth rates are about a factor of 10 faster in air than in vacuum.

Most of the effects of interaction of the fatigue cracks with creep cracks can be qualitatively rationalized by recognizing that the scale of the prior intergranular creep damage is nearly the same as the size of the reversing plastic zone for the fatigue crack, producing effective interaction between the two. The dramatic slowing down of the fatigue crack at 700°C in damaged material is most likely a result of additional cyclic grain boundary sliding which produces an even greater increase in the effective scale of the intergranular creep cracks by bridging them together. Quantitatively accurate models of these effects have proved to be difficult to obtain, however, due to the complexity of the interactions of microcracks with fatigue cracks under fully plastic conditions. From an overall engineering point of view it is useful to observe that the acceleration or deceleration of the fatigue crack by rather extensive intergranular creep damage is of the same order as the specimen to specimen variations of crack growth rate due to random microstructural variations or variations in creep resistance. The unambiguously measured effects reported above were possible to obtain only in material that had a damage gradient built into a constant stress intensity specimen. L. James (3), performing more standard experiments, could not separate the observed effect from specimen to specimen scatter.

C. Additional Investigations:

Parallel to the major investigations, the results of which have been outlined above, some additional small investigations were undertaken on an exploratory basis. These were:

a. Computation of interfacial stress concentrations around non-deformable particles in both non-hardening and linearly hardening plastic matrices. (A. S. Argon).

b. Preliminary experimental investigations of plastic deformation and creep deformation in directionally solidified nickel containing

tantalum carbide fibers, demonstrating strong instabilities in deformation and strain localization when deformed in orientations other than parallel to the fiber direction (A. S. Argon).

c. Theoretical investigation of creep in heterogeneous alloys containing different volume fractions of relatively equiaxed second phases having greater creep resistance, with and without sliding interfaces. (I. Chen).

References

(1) J. W. Hutchinson, J. Mech. Phys. Solids, 16, 13, 1968.

(2) A. N. Stroh, Proc. Roy. Soc., (London) A223, 404, 1954.

(3) L. A. James, J. Testing and Evaluation, 1, 1, 1973.

III. List of Participants

a. Ali S. Argon, Professor of Mechanical Engineering, principal investigator.

b. Iwei Chen, Graduate Student, Materials Science and Engineering (fellowship).

c. Josef Gertner, Graduate Student, Mechanical Engineering (fellowship).

d. Chun W. Lau, Graduate Student, Mechanical Engineering (Research Assistant).

IV. Advanced Degrees Granted

1. J. Gertner, "Fatigue Crack Propagation in 304 Stainless Steel with High Temperature Creep Damage", Sc.D. Thesis in Mechanical Engineering, M.I.T., October 1977.
2. Chun W. Lau, "Intergranular Hole Formation in Creep at Elevated Temperatures, Sc.D. Thesis in Mechanical Engineering, M.I.T., January 1978, (expected date of completion).

V. Publications Resulting from this Research.

1. A. S. Argon, "Formation of Cavities from Nondeformable Second Phase Particles in Low Temperature Ductile Fracture", Journal of Engineering Materials and Technology, 98, 60-68, 1976.

2. A. S. Argon, "Stresses in and Around Slender Elastic Rods and Platelets of Different Modulus in an Infinite Elastic Medium under Uniform Strain at Infinity". Fibre Science and Technology, 9, 265-275, 1976.
3. C. W. Lau and A. S. Argon, "Stress Concentrations Caused by Grain Boundary Sliding in Metals Undergoing Power-Law Creep, Fracture 1977, edited by D. M. R. Taplin, (U. Waterloo Press: Waterloo Canada) vol. 2, 595-602, 197.
4. A. S. Argon and W. J. Shack, "Theories of Fibre Cement and Fibre Concrete", in Fibre Reinforced Cement and Concrete, edited by A. Neville, (The Contruction Press Ltd: Lancaster, U.K.), 39-53, 1975. (Note this paper does not represent research done under this contract. Credit is given to the present contract only because it has utilized many of the theoretical results obtained in the course of research on this contract).

There will be additional publications on:

5. "Method of Computation of Stress Concentrations around Particles on Sliding Grain Boundaries";
6. "Nucleation of Holes on Interfaces of Particles on Sliding Grain Boundaries";
7. "Interaction of Fatigue Cracks with Intergranular Creep Cracks in 304 Stainless Steel", which will give partial credit to the terminated contract.

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13. ABSTRACT

The development of interfacial stresses around non-deformable particles have been investigated under several different conditions:

a) either directly imbedded into a plastically deforming medium or a medium creeping according to a power law;

b) situated on a sliding boundary that transmits only normal tractions and separates media creeping according to a power law;

In addition, stresses around triple grain boundary junctions have been computed across those boundaries normal to the tensile stress, adjoining two other boundaries transmitting only normal traction.

The changes in the fatigue crack propagation rate in 304 Stainless Steel due to previously introduced intergranular creep cracks have been investigated at both room temperature and 700°C in both air and vacuum. The measured accelerations or decelerations of the fatigue crack are no larger than the specimen to specimen scatter observable in normal fatigue research.

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